A CASE STUDY ON THE USE OF DIGITIZED CLOUD BRIGHTNESS DATA TO REPRESENT LARGE-SCALE CONVECTION IN THE TROPICS.

Bruce B. Edwards

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

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by

Bruce B. Edwards

Thesis Advisor: C.-P. Chang

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A Case Study on the Use of Digitized Cloud Brightness Data to Represent Large-Scale Convection in the Tropics

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Bruce B. Edwards
Lieutenant, United States Navy
B.S., Florida State University, 1968

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ABSTRACT

Digitized cloud brightness data for July 1969 are examined to determine the degree of relationship between organized brightness patterns and the large-scale convection field in the tropical western North Pacific. Correlation coefficients between kinematically computed vertical motion fields and cloud brightness are generally low, except for a few notable days. This may be due to the quality of the available data, particularly the vertical motion field. Nevertheless, indications of better correspondence between the two fields are noted late in the month for the western portion of the region, for the latitude band between 10°N and 20°N.

Examination of time-longitude sections reveals a close association between propagating brightness patterns and vertical motion fields, indicating that the former are reflections of synoptic wave passages, rather than simply inactive clouds advected by zonal flow.

In view of the potential usefulness of such satellite data, a technique is proposed that uses satellite cloud data to objectively determine the large-scale tropical flow.

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I. INTRODUCTION

Tropical analysis has long suffered from a sparse observational network. It is natural to hope to supplement this network with available satellite data. Digitized cloud brightness data, acquired by the Advanced Vidicon Camera Systems of the operational satellite system, have been available since 1967. Methods of utilizing this data on an operational basis may contribute significantly toward improving synoptic-scale analysis of the tropics.

Satellite photographs of tropical regions reveal that much of the tropical cloudiness is in the form of large, connected masses of very bright clouds. These masses are composed of many individual cumulus clouds, whose extensive cirrus canopies account for their brightness. Through the use of satellite photographs, these large, bright cloud masses, or "cloud clusters" as they are now called, have received considerable attention in recent years.

Chang (1970), using time-longitude series of satellite photographs, found that many cloud clusters over the tropical Pacific are well organized and have characteristics resembling those of synoptic-scale westward propagating wave disturbances. Reed and Recker (1971) showed further evidence that the propagating cloud clusters are linked to synoptic-scale waves in the wind field, while Williams (1970), using a compositing technique, examined the mean structure of trade wind cloud clusters in the western North Pacific. Wallace (1971) also found a high degree of organization to cloud brightness patterns, with many patterns maintaining their identity over a period of weeks.

Work such as this has indicated that clusters represent the organized cumulus convection whose importance to large-scale tropical motions is well recognized. On the belief that clusters do represent organized convection, attempts to utilize cloud brightness, either directly from satellite photographs or in a digitized form, have mainly taken two directions: 1) to estimate rainfall, and 2) to indicate vertical motion.

Precipitation, while important in its own sake, also indicates the spatial extent of convection and updraft intensity, as well as latent heat release. Attempts to estimate rainfall using satellite data have been reviewed by Martin and Scherer (1973). Specifically, Woodley and Sancho (1971) and Woodley et al (1972) have attempted to relate rainfall to cloud brightness using sophisticated methods to correct or normalize the raw cloud brightness data before using it quantitatively.

In examining digitized cloud brightness data, Wallace (1971) found a tendency for it to be well correlated with certain indicators of disturbed weather, particularly vertical motion, and he emphasized his belief that digitized brightness data may be the best available indicator of disturbed weather in the tropics. Wallace and Chang (1972) applied digitized cloud brightness data to the study of tropical wave disturbances. They found fairly good correspondence between area-averaged cloud brightness and vertical motion, and expressed their belief that it may be possible to obtain an estimate of the vertical motion field over the tropics from the cloud brightness data alone.

If, as these studies suggest, a vertical motion field over the tropics can be obtained from brightness data alone, then it may be possible to derive the large-scale tropical flow field even over regions where wind observations are extremely sparse.

This study is an attempt to empirically relate the organized brightness to the large-scale convection field through the vertical motion field. The objectives of this study are 1) to examine the relationship between digitized cloud brightness and the large-scale convection field in the tropics, and 2) to propose a technique to improve the analysis of data-void tropical regions through the use of digitized cloud brightness data.

The area selected for this study is the tropical western North Pacific, from the equator to 30°N, 125°E to 180°. The region includes the Caroline and Marshall Islands with nine rawinsonde stations. Figure 1 shows the region and the rawinsonde network.

Digitized cloud brightness and upper-level wind data used in this study were provided by the National Center for Atmospheric Research (NCAR). The cloud brightness data, acquired by NCAR from the National Environmental Satellite Service (NESS), are digitized values averaged for 5° x 5° latitude-longitude squares. The units of brightness are arbitrary, but have been designed to show a linear rate of change from black to white within a scale of zero to ten. (This data, although an average, will be referred to as raw cloud brightness data in this paper.) Upper-level component winds at the 700, 500, 300, 250 and 200 mb levels were acquired by NCAR from the National Meteorological Center (NMC) tropical grid analyses.

These winds are also on 5° x 5° latitude-longitude grids, and are the result of analyses based on all tropical rawinsondes, wind soundings, aircraft observations, and some few winds deduced from cloud drift as seen from satellite photographs. NCAR also provided rawinsonde observations for the region of study, which were used to obtain surface data and low-level wind fields.

The time period of the study is July 1969, which contained 23 days of useful data. The 0000 GMT wind data were selected as being closest to the time of the satellite observation. The satellite in operation during July 1969 was ESSA IX.

II. RELATIONSHIP BETWEEN CLOUD BRIGHTNESS AND THE LARGE-SCALE CONVECTION FIELD

To determine the relationship between cloud brightness and the large-scale convection field, the digitized cloud brightness data is compared both subjectively and objectively to the vertical p-velocity field (ω). The vertical motion field is chosen because Wallace's (1971) results indicate the potential for good correlation. The raw cloud brightness data as available from NESS is used with no attempt to adjust it for radiation geometry considerations or instrument characteristics.

Fields of vertical motion ω and divergence are computed kinematically. Divergence computations are performed at the 900, 700, 500, 300, and 200 mb levels by simple finite-differences over the 5° x 5° grid. Vertical velocities are constrained by the boundary conditions $\omega = 0$ at 1000 and 100 mb. The correction to satisfy these boundary conditions on ω is distributed linearly with pressure to result in adjusted divergence values at the stated levels, and values of ω at the 900, 800, 600, 400, 300, and 200 mb levels, in addition to the boundary values. The validity of such calculations on a 5° x 5° grid is undoubtedly questionable. However, for the purpose of correlating the vertical motion with cloud brightness, an approximate indication of the vertical motion should be adequate to at least show whether the correlations tend to be high or low. Furthermore, the computed divergence profile in areas of organized brightness shows a deep layer of convergence with a thin layer of divergence above, and both the

divergence profiles and the vertical motion profiles in areas of organized brightness show generally good agreement with the results found by Williams (1970) and others, thereby lending some confidence to the calculations. Nevertheless, in view of the calculations, more confidence is placed in the directly observed fields of cloud brightness.

A. SMOOTHING OF CLOUD BRIGHTNESS FIELDS

Intuitively, the best correspondence between cloud brightness and vertical motion should occur when the clouds are well organized, active and deep -- indicating strong rising motion through much of the troposphere. The results of Woodley et al (1972) support this. In examining the correspondence between radar echoes (which indicate precipitation and therefore probable areas of deep convection) and cloud brightness, they found the best correspondence when clouds are young and active and the worst when clouds are old and dying. The brightness patterns should, therefore, be maintained in both time and space. Small, isolated bright spots will be undesirable, as well as dissipating brightness patterns no longer supported by convection. To separate small, isolated bright spots from the organized convective brightness, hopefully retaining only brightness patterns representing cloud clusters, the brightness data are subjected to several elementary smoothing techniques. It is found that simple area-averaging of surrounding grid values with various weighting applied to the central value is adequate to emphasize the larger, organized brightness areas and wipe out isolated bright spots.

B. SUBJECTIVE COMPARISON OF CLOUD BRIGHTNESS TO VERTICAL MOTION FIELD

The unmodified and smoothed brightness fields are analyzed, or contoured and then compared with the analyzed vertical motion fields at

the 600 and 300 mb levels, which were selected as representative of the low and upper-level fields, respectively. The brightness fields show good organization, with many brightness patterns maintaining their identity as they move westward across the region of study. The vertical motion fields show alternating patterns of rising and sinking motion that propagate westward with time and have spatial characteristics typical of synoptic-scale wave disturbances. This apparent wave structure becomes most evident at the 300 mb level during the latter part of the month. These wave disturbances and their relationship to the organized cloud patterns will be discussed in more detail later.

The best correspondence between brightness and vertical motion appears when the rising motion is deep, extending up through the 300 mb level. Accordingly, in most cases, the 600 mb comparisons reveal nothing that is not apparent at the 300 mb level. In fact, the relative orientation and size of the patterns appear better at the 300 mb level.

Figures 2, 3 and 4 show the contoured fields of 600 mb vertical motion, 300 mb vertical motion and cloud brightness, respectively, for 27 July 1969. Figures 5 and 6 show the 300 mb vertical motion and the cloud brightness field, respectively, for 29 July 1969. The figures for 27 July compare well, and in fact, exhibit the best correspondence encountered during the month. The figures for 29 July are more typical. Note that there are essentially three areas of strong, organized brightness, none of which compare well to the vertical motion field. The contoured cloud brightness fields shown are fields of raw brightness data. While the smoothed brightness fields are more pleasing

to the eye, the raw brightness fields are found to lend themselves more readily to visual comparison with the vertical motion fields.

Comparison of contoured fields for the entire month reveals the following:

a. Better correspondence between areas of organized brightness and centers of rising motion is seen for the western portion of the region and between the latitudes of 10°N and 20°N. In fact, the eastern portion possesses comparatively few organized brightness patterns, exhibiting generally a widespread area of zero or low brightness. This increase in organization and intensity may be a reflection of the westward intensification of cloud systems found by Chang et al (1970) and Reed and Recker (1971) as wave disturbances move across the region of study. Sikdar et al (1972) also noted marked geographical variations in cloud activity over the Pacific.

b. The correspondence tends to improve toward the end of the month. Thus, the organization of the brightness patterns may vary considerably even within a season, or there may be a steady increase in the organization through the late summer.

c. While Wallace's (1971) results indicated a good phase relationship between brightness and vertical motion, this is not evident in this study. However, the brightness centers are displaced both east and west of the centers of rising motion, which suggests that the fault may lie in the inaccuracies of the vertical motion calculations. Furthermore, there is a time difference between the two fields which is ignored in this study. The vertical motion field is computed from 0000 GMT data. The time of the satellite observation varies across

the region, but generally is within two to three hours of the 0000 GMT observations.

d. Many of the brightness patterns exhibit a southwest to northeast tilt, which seems to correspond to the usually observed tilt of synoptic waves in the tropics, as summarized by Wallace (1971).

e. Except on certain days and for limited regions, the correspondence between areas of brightness and areas of rising motion cannot be considered satisfactory. In general, for this study, centers of organized brightness may appear in regions of either rising or sinking motion.

C. OBJECTIVE COMPARISON OF CLOUD BRIGHTNESS TO VERTICAL MOTION FIELD

To objectively determine the relationship between cloud brightness and the vertical motion field, scatter diagrams and simple linear correlation coefficients are obtained. Due to the poor quality of the computed vertical motion fields, the objective is not necessarily to seek high correlation coefficients, but rather to determine if the correlation tends to be generally high or low.

Vertical motion fields at the 800, 600, 400, and 300 mb levels are used for the correlations with both the raw and smoothed brightness fields. The correlations are computed on both a daily basis and for the month. In addition, on the basis of the subjective comparisons, correlations are obtained between the vertical motion and the smoothed brightness for just the western portion (125°E to 155°E) of the region, and for only the last ten days of the month.

Since the subjective comparisons suggested that the best correspondence exists when the rising motion is deep, the correlations are

expected to be generally negative at all levels. That is, increasing cloud brightness as the vertical motion ω becomes more negative (stronger rising motion). This is indeed the case. The highest correlation is obtained most frequently at the 300 mb level. In fact, in 92 percent of the cases, the best correlations occur at the upper levels, at either 300 or 400 mb.

Figures 7 and 8 show scatter diagrams of smoothed cloud brightness versus 600 and 300 mb vertical motion, respectively, for 27 July 1969. Figure 9 shows the scatter diagram for the raw cloud brightness versus the 300 mb vertical motion on 27 July 1969. As mentioned earlier, this day illustrates the best correspondence found during the month. The correspondence is best at the 300 mb level, and for the smoothed brightness case. While the scatter is greater at 600 mb, the correspondence is still reasonably good. The linearity is particularly good for the smoothed brightness data.

A more typical case is shown in Figures 10 and 11, which are scatter diagrams of smoothed cloud brightness versus 600 and 300 mb vertical motion, respectively, for 29 July 1969. Note a great deal more scatter at the 600 mb level than at the 300 mb level, and note also that the scatter at the 300 mb level is about a line of nearly zero slope. In other words, the entire range of brightness values exists with both rising and sinking motions. This situation occurred quite frequently.

Another common situation is illustrated by Figure 12, wnich shows the scatter diagram of 300 mb vertical motion versus smoothed cloud brightness for 22 July 1969. There appear to be two groups of brightness values, one group of low brightness values and another of high

values with the split at around a value of 2.0. This suggested that establishing a "brightness threshold" by deleting brightness values less than a mean brightness value or an arbitrary value around 2.0, from the cloud brightness sample, might improve the correlations. However, as will be discussed later, such modifications do not actually improve the correlations.

Table I lists the correlation coefficients between the 300 mb vertical motion and the raw cloud brightness, the smoothed brightness, and the smoothed brightness for just the western portion of the region. This level produced the highest correlations. The coefficients are listed by day, for the month, and for the last ten days of the month. The following comments apply:

a. For the full grid, the daily sample size is 72. Panofsky and Brier (1965) describe an analysis of variance method to determine if a correlation coefficient is significant, i.e., if it is greater than that which could occur by chance alone. Using this method, the correlation coefficients must be greater than about 0.24 to ensure significance at the 5 percent level and 0.30 at the 1 percent level. On this basis, ten of the 23 days for the smoothed brightness case show significant correlations at the 5 percent level, and five at the 1 percent level. For the western portion of the grid the daily sample size is 42. For this sample, the coefficients must be greater than 0.30 to ensure significance at the 5 percent level, and 0.38 at the 1 percent level. Thus, for the western portion, 11 days show significant coefficients at the 5 percent level and eight days at the 1 percent level. Although this difference is certainly small, it does suggest (as did the subjective comparisons) that generally the western portion of the

region for the area-averaged brightness has a higher degree of relationship to the vertical motion field.

b. The correlations are negative on all except two days, the first and the twelfth. These are days on which there are few centers of rising motion.

c. Subjectively, it is easier to compare brightness with vertical motion using the raw cloud brightness fields. Objectively, while smoothing in most cases improved the correlations, the improvement is quite small.

d. As suggested by the subjective comparisons, the correlations are higher during the latter portion of the month. (For the western sample, nine of the last ten days have coefficients which are significant at the 5 percent level of confidence.)

Thus, generally the correlation between organized brightness patterns and the vertical motion field for this study is quite low (only about half of the days show coefficients higher than that which could occur by chance alone). However, as noted above, there is a tendency for higher correlations to occur for certain regions and time periods.

Correlation coefficients were also computed for several modifications. For example, a "brightness threshold" was established. Brightness values less than the monthly mean of cloud brightness and arbitrary brightness values of one and two were deleted from the smoothed brightness sample. The remaining samples of brightness values were then correlated with the vertical motion field, and also with only the field of rising motion. In all cases, such modifications resulted in only slightly higher coefficients but reduced the sample size to one of questionable significance.

D. COMPARISON OF TIME-LONGITUDE SECTIONS

As mentioned earlier in this section, the analyzed fields of vertical motion exhibit wave disturbances which become particularly evident at the 300 mb level during the latter portion of the period of study, and many of the brightness patterns exhibit a tilt in the same orientation as that of synoptic-scale waves observed in the wind field. These results suggest that both fields may be organized by synoptic-scale waves. Thus, one may expect to find a better relationship between the two fields in a time-space domain corresponding to that of synoptic-scale waves. If this is the case, it may also provide an answer to a question addressed by Chang (1970) and Wallace (1972) regarding the westward propagating cloud patterns.

Chang (1970) and Reed and Recker (1971) suggested that propagating cloud patterns may be reflections of westward propagating synoptic-scale waves. However, Wallace (1972) noted that the westward propagating cloud patterns seen on time-composite satellite photographs generally move with nearly constant speed, but that the horizontal spacing between such clouds appears to be quite variable. In view of this "non-dispersive" phase speed, he expressed a doubt that these clouds are reflections of wave passages, but that, more likely, they are simply advected by zonal flow.

In order to examine these questions, time-longitude sections of the raw brightness and the fields of rising motion are compared for five-degree latitude bands. Figures 13 and 14 show, respectively, the sections of the cloud brightness and the rising motion for the 10° - 15°N latitude band. This latitude band is the most useful for

comparisons as other bands show fewer propagating cloud patterns. The path of westward moving brightness patterns can be quite easily traced from these sections. Several such paths are plotted as propagation lines in the brightness section (Figure 13), and then overlapped on the vertical motion section (Figure 14). It can be seen from the latter section that the cloud pattern generally propagates along an area of strong upward motion. Considering the inherent inaccuracies in the two fields and the time differences, this result may be viewed as a strong indication that the propagating cloud patterns are indeed associated with synoptic wave passages. This is due to the fact that if they are simply inactive clouds advected by zonal flow, one would not expect such an associated upward motion tendency.

III. DESIGN OF OBJECTIVE TECHNIQUE THAT USES DIGITIZED BRIGHTNESS DATA

Although a firm relationship between satellite-observed cloud brightness and meteorological parameters has yet to be established, confidence must be placed in what is actually seen through the satellite camera. The visual indications that the dense cloud masses reflected in satellite photographs are related to active convection and large condensation heating can hardly be ignored. With the belief that such a relationship exists, and in view of the need and desirability of using satellite data to improve the analysis of a data-void tropical region, an objective technique has been designed. Although the model is still in the development stage, undergoing further modifications and testing, the basic design is outlined here to illustrate such a possible technique.

A. BASIC MODEL

The basic idea of the model is to consider that the horizontal divergence term is the forcing function in the vorticity equation, and to assume that the unknown divergence field may be replaced by a satellite-observed brightness field. The linearized vorticity equation is then integrated to yield a steady state perturbation stream function resulting from such forcing.

The vorticity equation in pressure coordinates may be written as

$$\frac{\partial}{\partial t} \zeta + u\frac{\partial}{\partial x} \zeta + v\frac{\partial}{\partial y} \zeta + v\beta = - (\zeta+f) \nabla \circ \vec{V} = (\zeta+f) \frac{\partial \omega}{\partial p} \qquad (1)$$

where

ζ = the relative vorticity

u = zonal component of the non-divergent flow

v = meridional component of the non-divergent flow

f = Coriolis parameter

$\beta = \partial f/\partial y$

$\partial\omega/\partial p$ = vertical differentiation of the vertical p-velocity

$\vec{V}$ = total horizontal wind vector

∇ = isobaric gradient operator

The thermodynamic energy equation is

$$\frac{\partial}{\partial t} T + \vec{V} \circ \nabla T + \omega S = Q \qquad (2)$$

where T is temperature, ω the vertical p-velocity, S the static stability, and Q the diabatic heating rate. Due to the usually small temperature fluctuations in the tropics, the first two terms of equation (2) may be neglected in comparison to the heating term. Thus,

$$\omega S \doteq Q \qquad (3)$$

which is a statement of balance between diabatic heating and adiabatic cooling. Substituting (3) into the right hand side of (1), the divergence at a level becomes

$$\frac{\partial\omega}{\partial p} = \frac{1}{S}\frac{\partial Q}{\partial p} = \frac{Q_o}{S}\frac{\partial\eta}{\partial p} \qquad (4)$$

where Q_o is a measure of the magnitude of the heating, and $\partial\eta/\partial p$ represents the vertical gradient of the heating profile. The parameter Q_o

is assumed to be proportional to the satellite-observed cloud brightness and thus may be empirically related to the brightness field. The term $\partial\eta/\partial p$, for simplicity, is specified as a constant based on observational studies by Reed and Recker (1971), Williams (1970), and Wallace (1971). Expression (4) may then be viewed as the known forcing for the vorticity equation (Chang, 1973).

For initial testing of the model, the simplest and most direct method is to relate the brightness empirically to the 300 mb divergence field by a proportionality factor. This brightness forcing may then be substituted for the horizontal divergence term in Equation (1).

Assuming that the basic state of each parameter is a function only of time and the y-axis, the linearized vorticity equation may be written as,

$$\frac{\partial}{\partial t} \nabla^2\psi' + \bar{u} \frac{\partial}{\partial x} \nabla^2\psi' - \frac{\partial\psi'}{\partial x} \frac{\partial^2\bar{u}}{\partial y^2} + \beta \frac{\partial\psi'}{\partial x} = (f - \frac{\partial\bar{u}}{\partial y}) B' + \nabla^2\psi'\bar{B} - D\zeta' \quad (5)$$

where primes denote perturbation quantities, bars denote basic state quantities, ψ is the stream function, B represents the brightness as related to divergence, and D is a damping term. The damping term is included on the basis of a study by Holton and Colton (1972) of the vorticity balance at 200 mb in the tropics, wherein they found that rather strong damping is necessary to achieve realistic stream function fields. This damping may be interpreted as due to the vertical transport of vorticity by cumulus convection. An additional term, $\zeta'B'$, not shown in (5) may be included with no difficulty since it is still linear in computation if B' is specified.

The corresponding finite-difference equation is as follows,

$$(\nabla^2\psi_{i,j})^{t+1} = \frac{(\nabla^2\psi_{i,j})^{t-1} * [1+\Delta t(\bar{B}-D)]}{[1 - \Delta t\ (\bar{B} - D)]} + \frac{2\Delta t}{[1-\Delta t(\bar{B}-D)]} * \{ (\frac{-\bar{u}m}{2d}) * \ldots$$

$$\ldots (\nabla^2\psi_{i+1,j} - \nabla^2\psi_{i-1,j}) + (\frac{m}{2d}) * (\psi_{i+1,j} - \psi_{i-1,j}) * (\bar{u}_{j+1} - 2\bar{u}_j + \bar{u}_{j-1}) \ldots$$

$$\ldots + (-\frac{\beta d}{2m}) * (\psi_{i+1,j} - \psi_{i-1,j}) + (\frac{B'd^2}{m^2}) * [f - \frac{m}{2d}(\bar{u}_{j+1} - \bar{u}_{j-1})]\}^t \qquad (6)$$

where the primes have been dropped for convenience, superscripts denote the time step, m is the map factor, d the grid distance, and the other terms are as previously defined. This equation requires a mean zonal wind, whose determination is a major problem. However, it is expected that monthly averages of observed data will prove adequate.

Equation (6) may now be integrated over a data-void region to obtain a steady state stream function field for the region if appropriate boundary conditions for the stream function are given. Thus, applying the model to a data-void region requires a judicious selection of the region itself. In most cases, data-void regions are bounded (although, not ideally) by areas with adequate wind information, typically island groups or edges of continents. A data-void region may, therefore, be designed as a rectangular area or "box" surrounded on all four sides by boxes of arbitrary size within which there is wind information. If stream functions on the boundaries of these data-rich boxes can be obtained, the values on the sides of these boxes which are adjacent to the data-void region may then be used as boundary conditions for the data-void region.

To obtain stream functions on the boundaries of the boxes, which are adjacent to the data-void region, thereby obtaining boundary

conditions for the data-void region, a method suggested by Hawkins and Rosenthal (1965) to compute stream functions using available wind data is employed. In addition to the outer boundary of each box, the method also uses the immediate inner boundary. To avoid reducing the area of the box, and to increase the finite-difference accuracy, all fields are first reduced from a 5° x 5° latitude-longitude grid to a 2.5° x 2.5° latitude-longitude grid by simple interpolations. The Helmholtz equation

$$\vec{V} = \hat{k} \circ \nabla\psi + \nabla\chi \ , \qquad (7)$$

is used to separate the horizontal wind field into a purely rotational part (ψ, the stream function) and a purely divergent part (χ, the velocity potential). Equation (7) can be written in tangential coordinates as

$$\frac{\partial\psi}{\partial s} = -v_n + \frac{\partial\chi}{\partial n} \qquad (8)$$

and

$$\frac{\partial\psi}{\partial n} = v_s - \frac{\partial\chi}{\partial s} \qquad (9)$$

where n denotes the outward normal direction, and s the tangential direction. With these equations, the procedure to obtain boundary conditions is outlined in the following six steps:

(i) Relax $\nabla^2\chi = \nabla \circ \vec{V}$, using $\chi = 0$ on the outer boundary, to obtain χ over the grid.

(ii) Calculate $\partial\chi/\partial n$ on the inner boundary using center-differences.

(iii) Integrate Equation (8) trapezoidally around the inner boundary to obtain ψ along the inner boundary.

(iv) Calculate $\partial\chi/\partial s$ on the inner boundary using center-differences.

(v) Integrate Equation (9) trapezoidally from the inner to the outer boundary to obtain ψ on the outer boundary. Corner values are filled in by interpolation from the surrounding grid points.

(vi) Discard ψ on the inner boundary.

To summarize the application of the model, a data-void region is specified such that it is a rectangular area or box, and is surrounded by four adjacent boxes which contain wind information. The Hawkins and Rosenthal procedure is then applied to each of the adjacent boxes to obtain stream functions on the boundaries of these boxes. Stream function values on the sides adjacent to the data-void box, then become boundary conditions for the data-void region. The vorticity equation (Equation 6) is then integrated over the data-void region (using brightness data to represent the forcing) to yield steady-state stream function fields for the region.

IV. SUMMARY AND CONCLUSIONS

Digitized cloud brightness data for July 1969 are examined by subjective and objective means to determine the degree of relationship between organized brightness patterns and the large-scale convection field in the tropical western North Pacific. Daily vertical motion fields for the region are computed kinematically using analyzed wind fields based on 0000 GMT wind observations. Comparisons are then made between the satellite-observed cloud brightness fields and the fields of vertical motion.

The correlation coefficients between the two fields are low, in most cases. However, consistent tendencies of better correspondence between the two fields are noted:

a. The correspondence is almost always better at the 300 mb level. This is consistent with the assumption that brightness is related to deep convection.

b. The correlation shows an improvement toward the latter portion of the month. In the spectral studies summarized by Wallace (1971), late summer-early autumn seems to be the most active season for tropical disturbances. Thus, the period selected for this study may be too early in the season. Further study extending to later months may yield better results.

c. The correlation appears better in the westernmost portion of the region. Chang et al (1970) and Reed and Recker (1971) have shown the marked increase of wave amplitude as disturbances move westward

from the vicinity of the Marshall Islands. In general, the eastern portion of the region of study simply shows a lack of high brightness.

Particularly in the latter part of the month, the computed vertical motion fields possess wave-like patterns. A time-longitude section study of the two fields indicates a general correspondence between propagating brightness patterns and centers of rising motion. This result suggests that the westward propagating cloud patterns noted in satellite photographs are reflections of wave passages, rather than advected cloud systems.

Based on the assumption that a dense cloud mass is related to large latent heating, a vorticity equation model which may be used to diagnose large-scale tropical flow patterns using satellite cloud data was proposed. This model, which assumes a correspondence between the cloud data and the divergence field, is derived from simple thermodynamic arguments.

Concerning the correlation between brightness and convection parameters, major problems exist. First, the "ground truth" - the vertical motion field used in this study is difficult to obtain accurately from the available data. The kinematic method posses large errors, while the vorticity equation method, which is actually the basis for the objective scheme proposed, requires knowledge of the damping due to cumulus transport. (It may be possible to obtain this knowledge by experimenting with the objective technique described in Section III.) The thermodynamic energy equation approach to determine ω must be ruled out because of the near balance between adiabatic cooling and diabatic heating.

Secondly, Woodley and Sancho (1971), among others, have pointed out that large, bright cirrus canopies resulting from cumulus outflow may remain for relatively long periods after the active convection has ceased. These bright but dead clouds no longer represent the active convection, but are not removed by the area-averaging process. Smoothing in the time domain is necessary to remove these inactive clouds, and a successful objective technique may markedly improve the correlations.

It was observed in this study that, while the centers of organized brightness may agree in position with centers of rising motion, the brightness perimeter may extend further over areas of sinking motion (low level divergence) than can be justified by errors in the vertical motion calculations. Conceivably, edges of organized cloud patterns may be advected or dispersed away from the area of rising motion to such an extent that the correlations are significantly lowered.

As mentioned earlier, the vertical motion field and the brightness field were not observed at the same time. Although the two fields for the region of study are within two to three hours of each other, the extent to which this time difference, uncorrected, effects the correlations is difficult to ascertain. However, Martin and Suomi (1971) found that uncorrected satellite cloud photographs could be used to study time changes in convection within three to four hours of local noon. Thus, it may be that cloud photographs taken close to local noon (which is the case for the region of study) do sufficiently indicate large-scale convection.

The digitized brightness data as available from NESS is subject to adjustments. Woodley and Sancho (1971) and Woodley et al (1972) in attempting to use brightness to estimate rainfall have found that in order to use the brightness quantitatively, they must first correct it--or normalize it, taking into consideration such things as cloud-satellite-sun geometry, satellite characteristics, and even printing techniques. These corrections require quite sophisticated techniques and are not, at present, being applied to the brightness data by NESS.

Finally, this study did not utilize infrared data. It is anticipated that future inclusion of infrared data should be useful in isolating the bright, cold-topped clouds which truly represent the organized convection.

TABLE I

Correlation Coefficients of Cloud Brightness vs 300 mb Vertical Motion

Date	Raw Brightness Full Grid	Smoothed Brightness Full Grid	Smoothed Brightness 125E - 155E
1 July 1969	.15	.13	.28
2	-.08	-.17	.08
3	-.24	-.24	-.26
6	-.21	-.22	-.39
8	-.12	-.15	-.10
9	-.13	-.16	-.06
10	-.10	-.14	-.08
11	-.08	-.09	-.01
12	.20	.23	.21
13	-.05	.02	-.23
15	-.08	-.25	-.25
17	-.23	-.27	-.22
19	-.23	-.23	-.32
20	-.24	-.24	-.42
21	-.22	-.19	-.33
22	-.30	-.33	-.30
23	-.32	-.41	-.45
24	-.22	-.26	-.37
25	-.32	-.30	-.39
26	-.36	-.40	-.55
27	-.60	-.62	-.63
28	-.34	-.33	-.51
29	-.19	-.30	-.39
Month	-.19	-.22	-.26
Last ten days	---	-.33	-.40

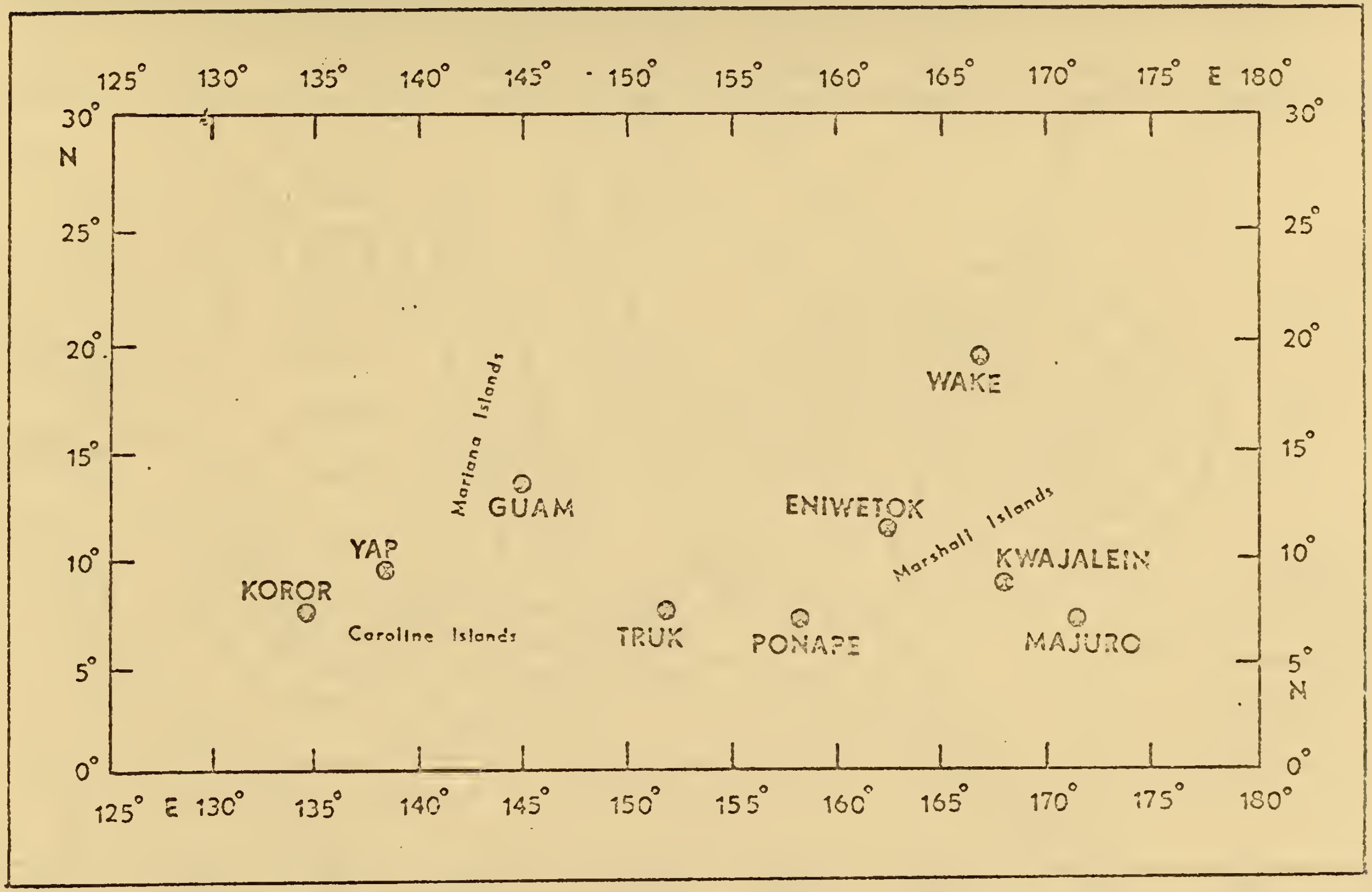

Fig.1. Region of study and observational network.

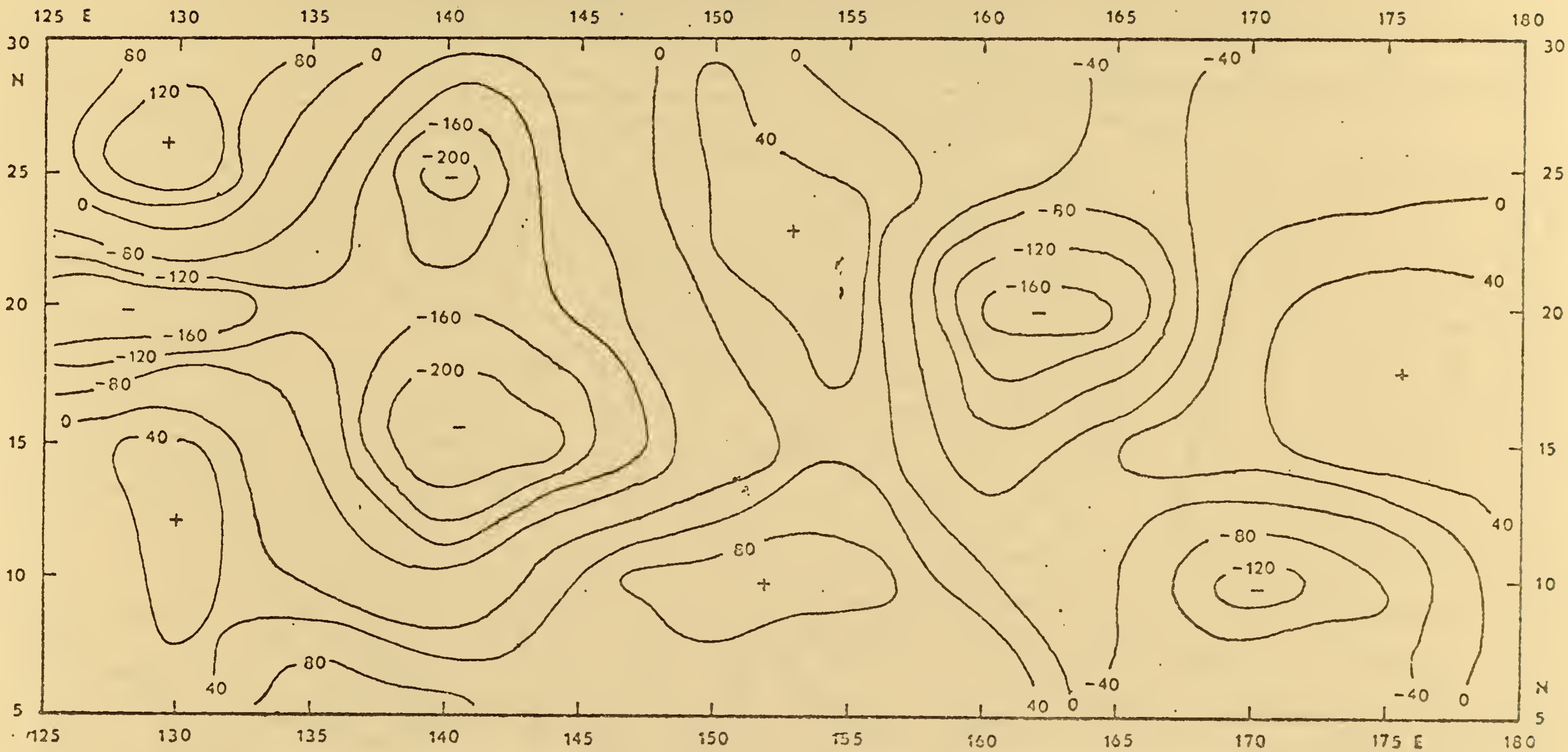

Figure 2. Vertical motion (mb/day) at 600 mb level for 27 July 1969.

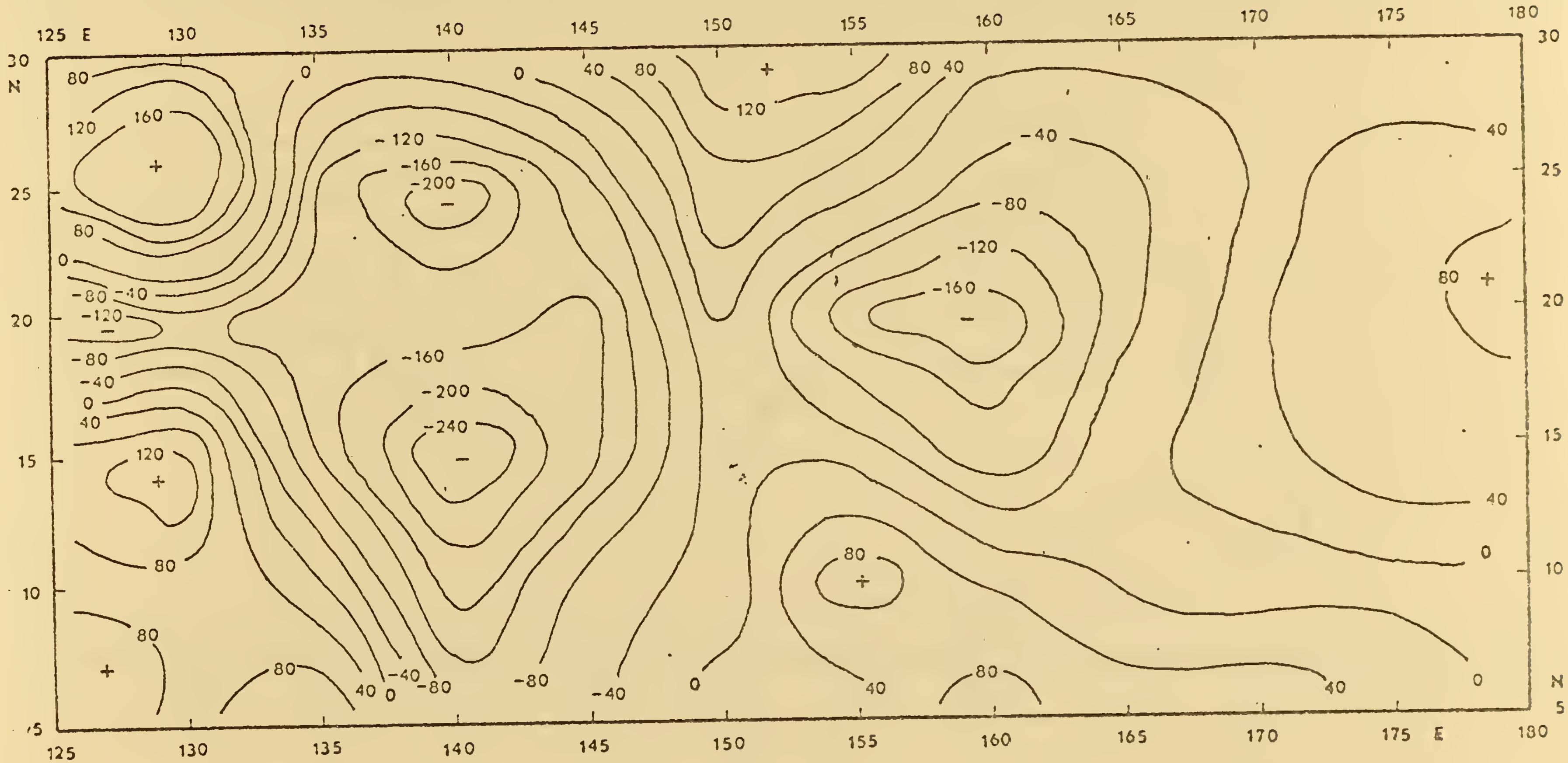

Figure 3. Vertical motion (mb/day) at 300 mb level for 27 July 1969.

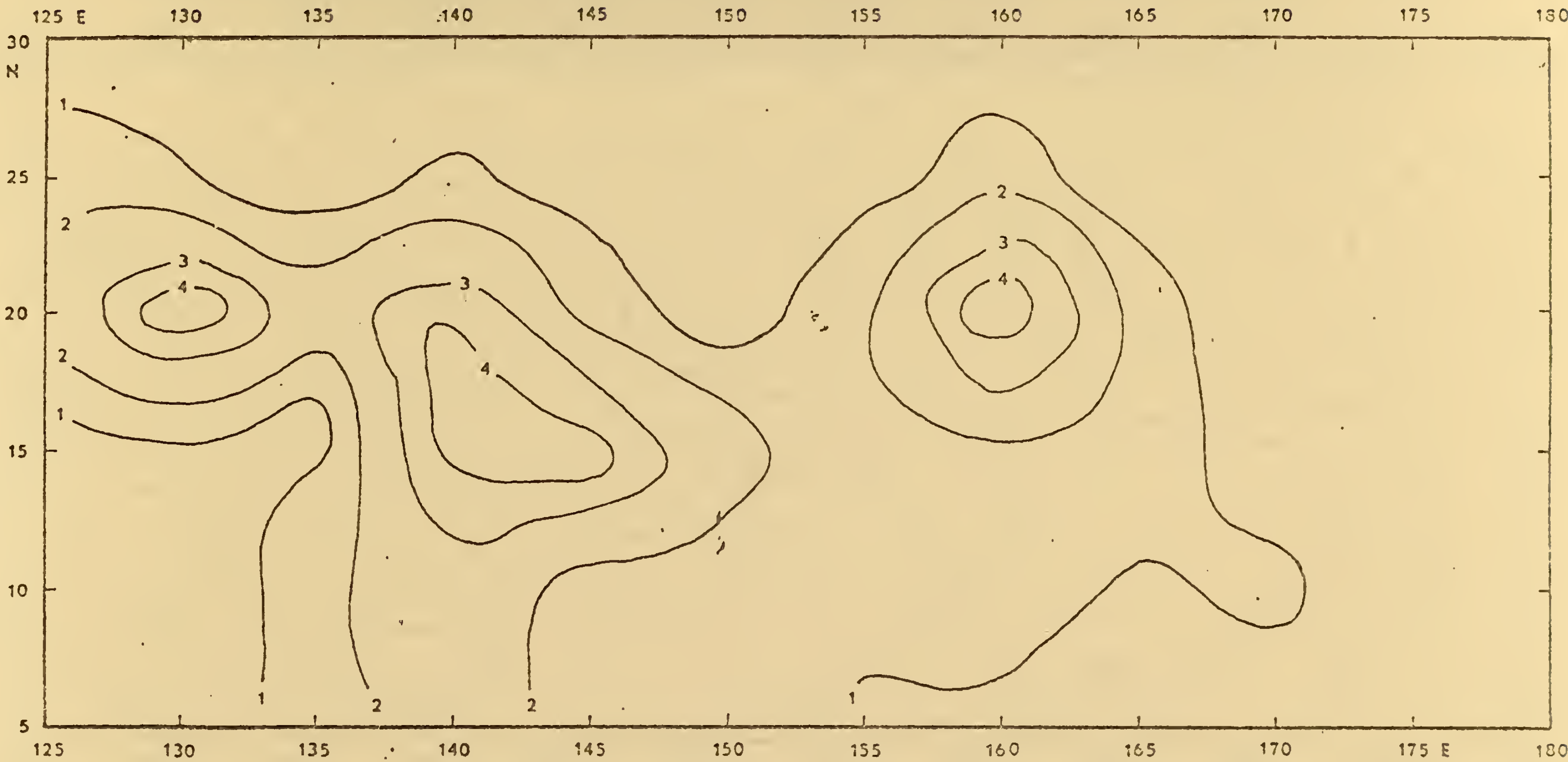

Figure 4. Raw cloud brightness field for 27 July 1969.

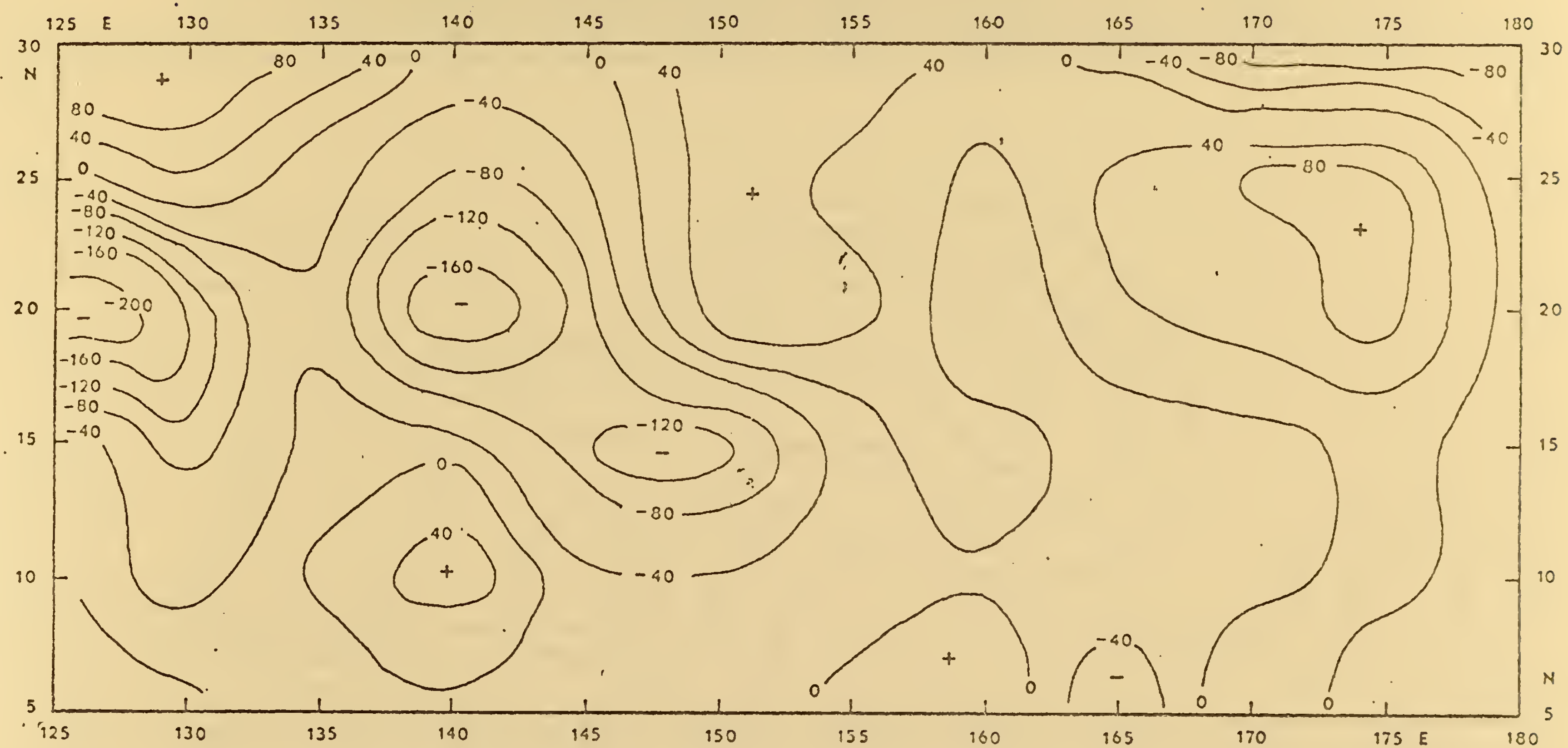

Figure 5. Vertical motion (mb/day) at 300 mb level for 29 July 1969.

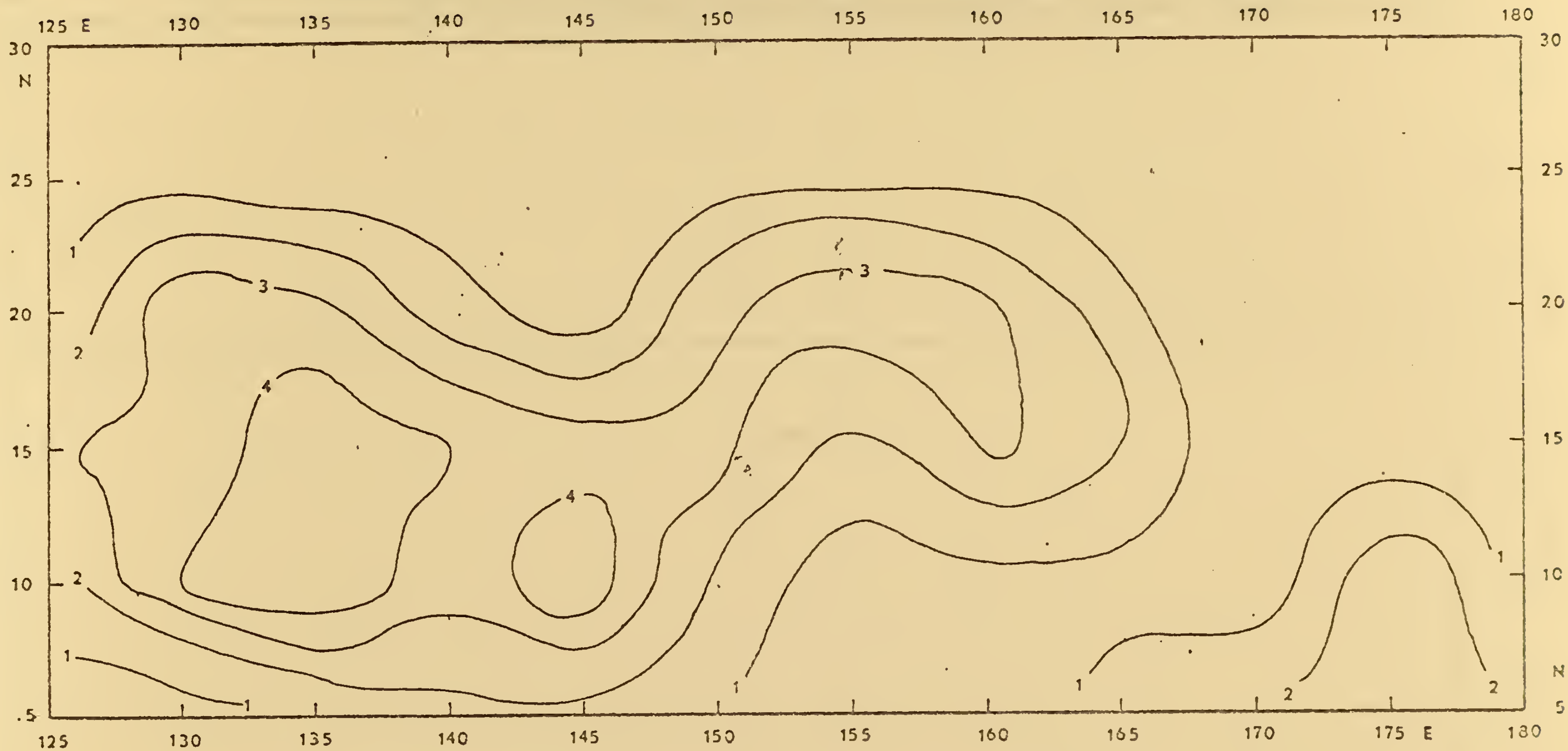

Figure 6.   Raw cloud brightness for 29 July 1969.

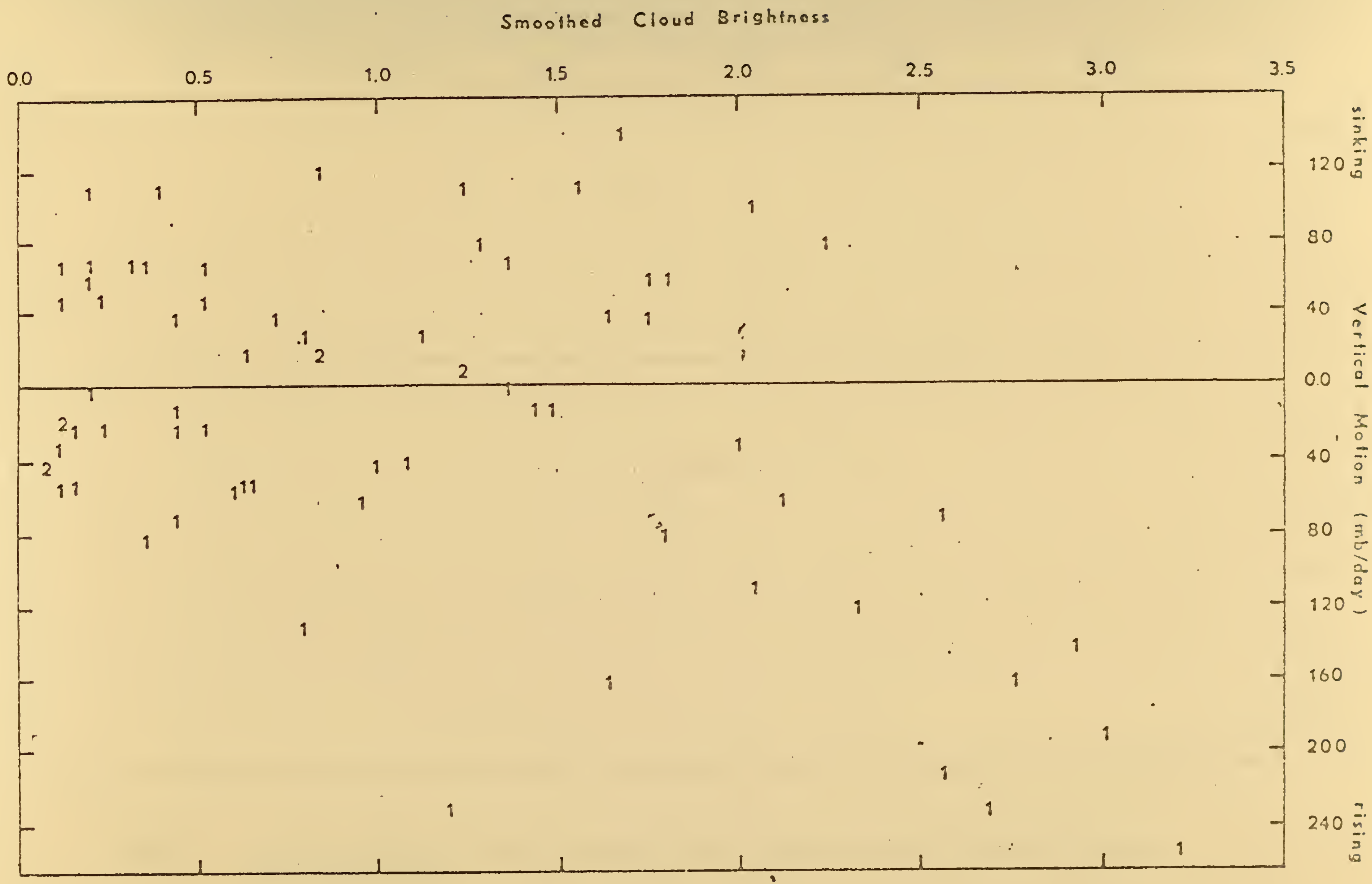

Figure 7. Scatter diagram of 600 mb vertical motion versus smoothed cloud brightness for 27 July 1969.

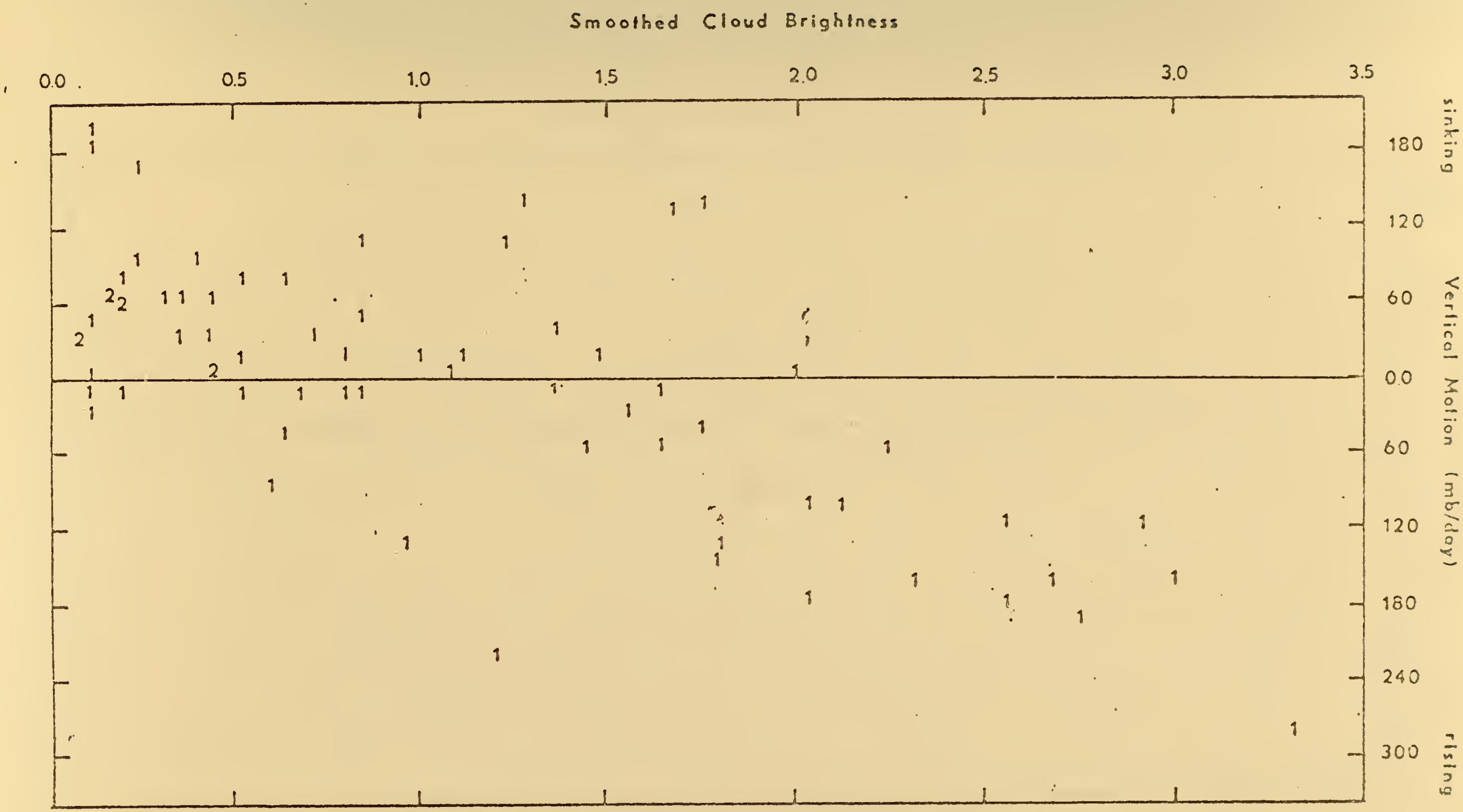

Figure 8. Scatter diagram of 300 mb vertical motion versus smoothed cloud brightness for 27 July 1969.

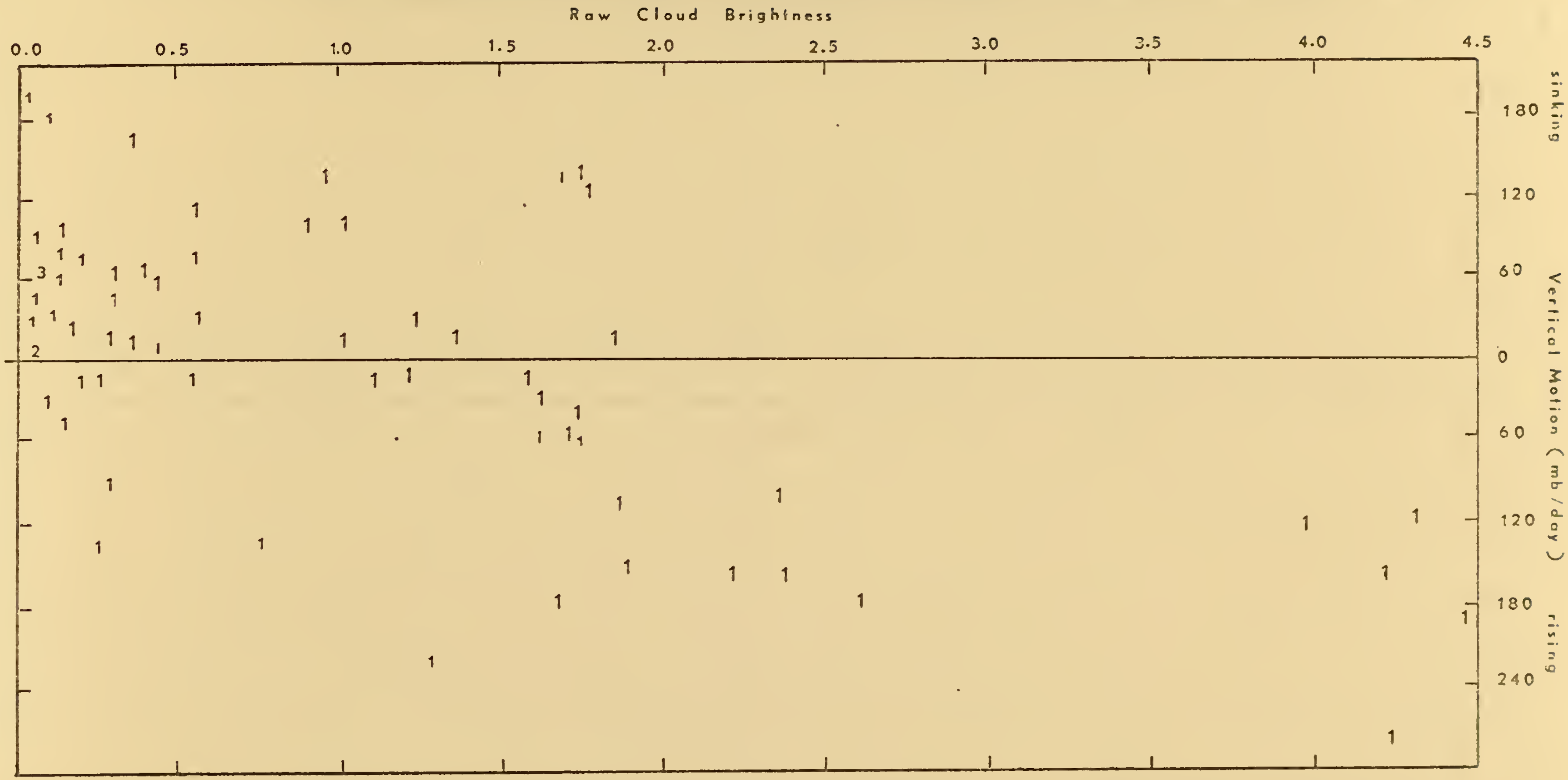

Figure 9. Scatter diagram of 300 mb vertical motion versus raw cloud brightness for 27 July 1969.

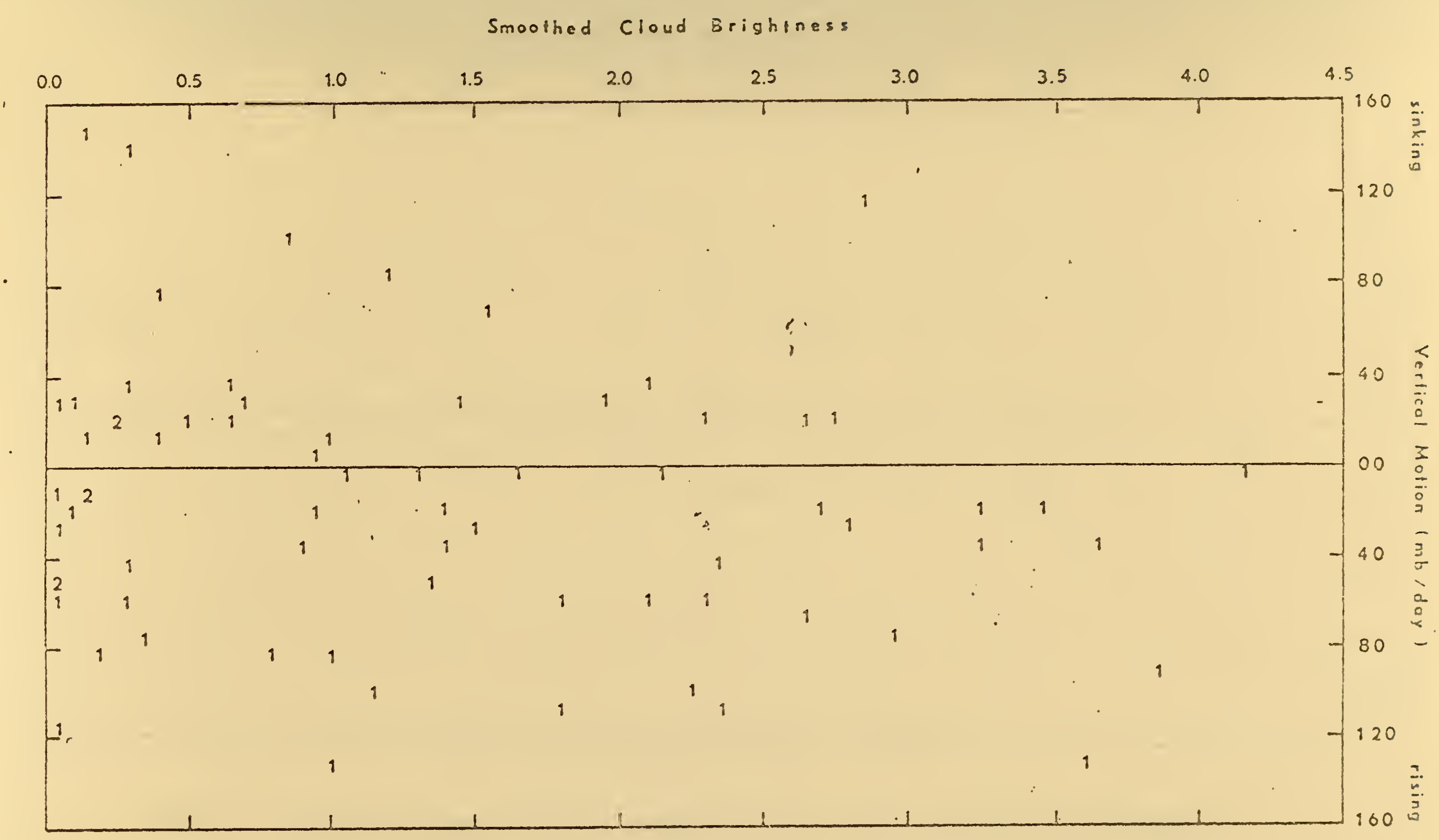

Figure 10. Scatter diagram of 600 mb vertical motion versus smoothed cloud brightness for 29 July 1969.

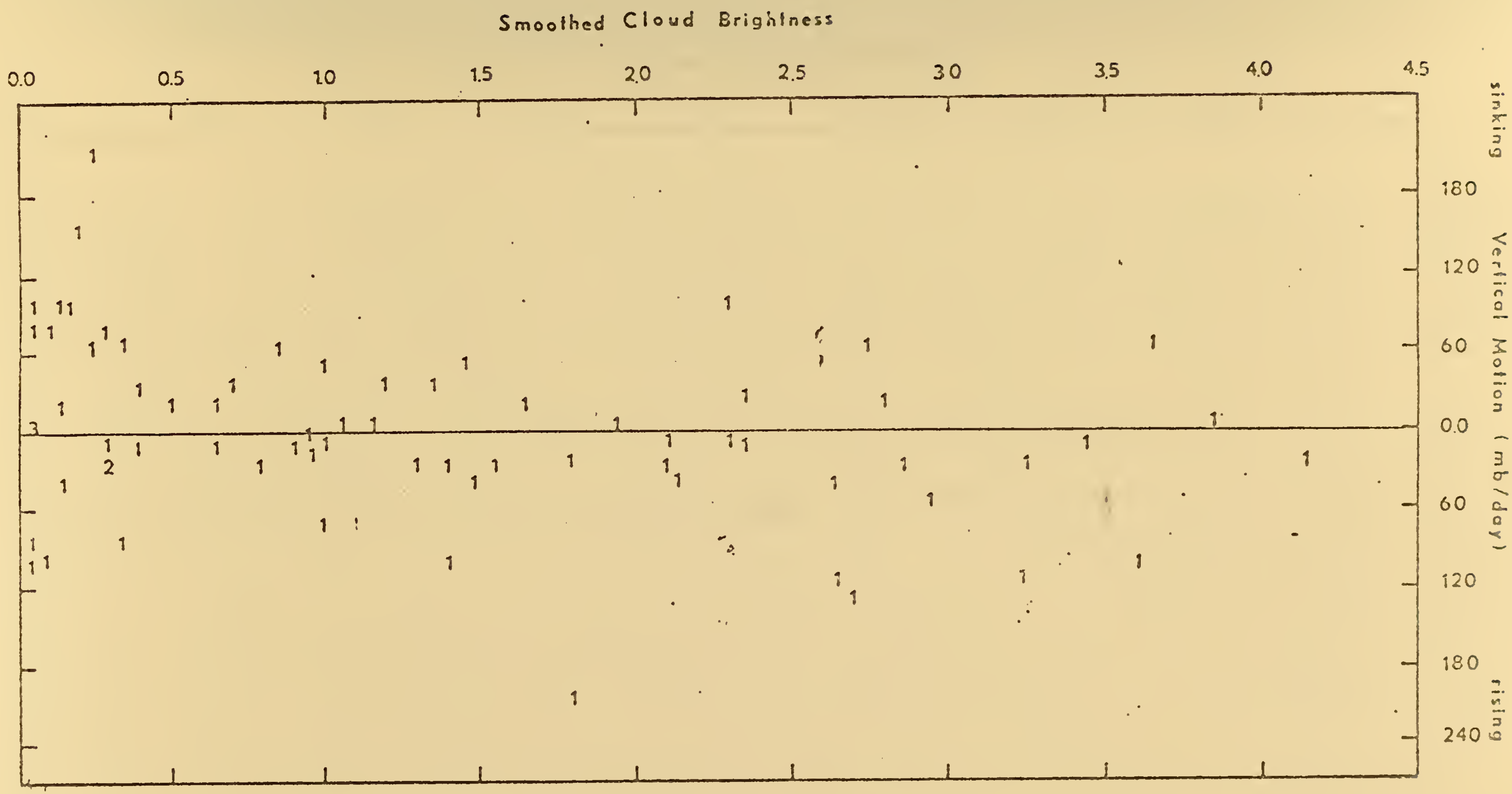

Figure 11. Scatter diagram of 300 mb vertical motion versus smoothed cloud brightness for 29 July 1969.

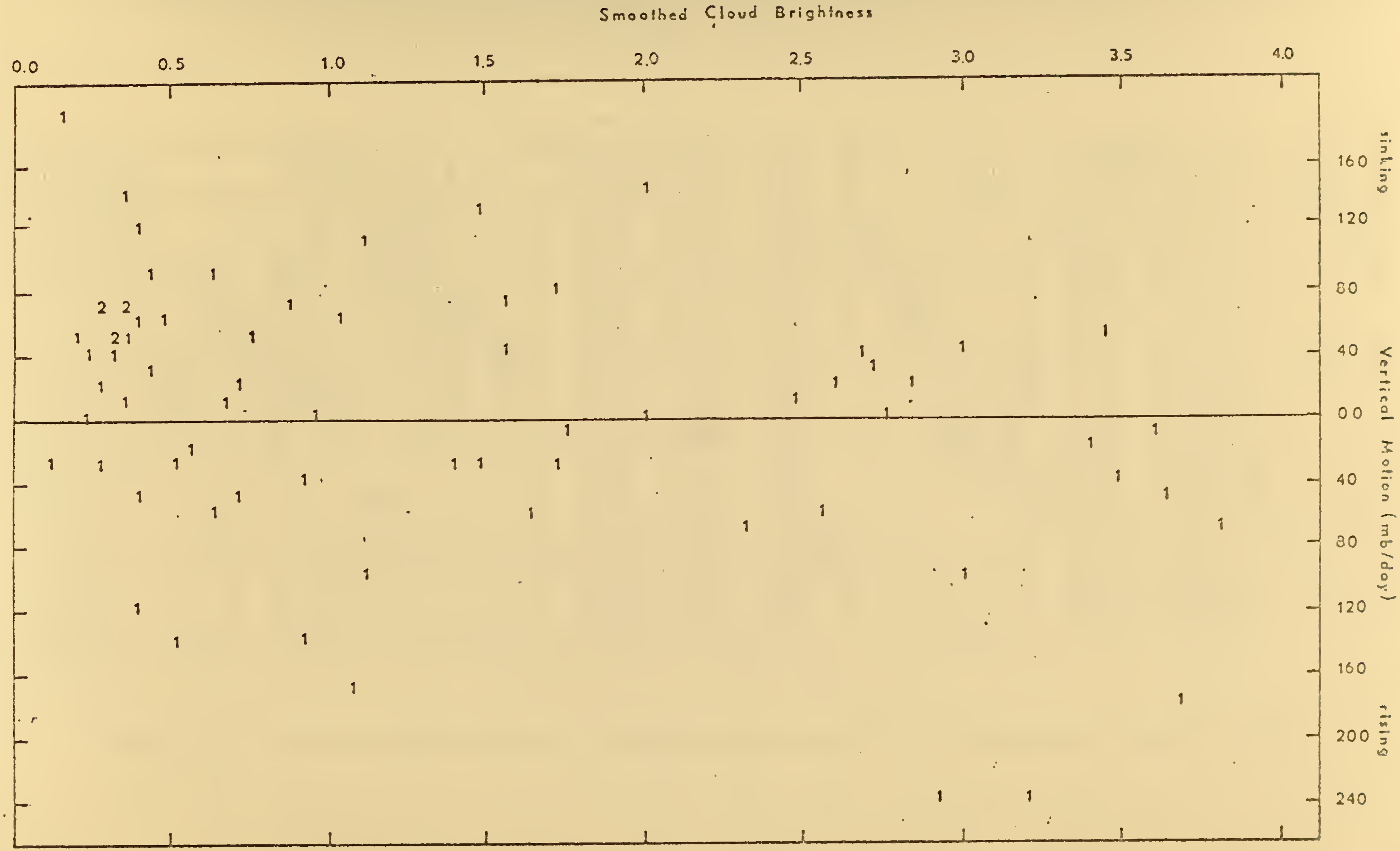

Figure 12. Scatter diagram of 300 mb vertical motion versus smoothed cloud brightness for 22 July 1969.

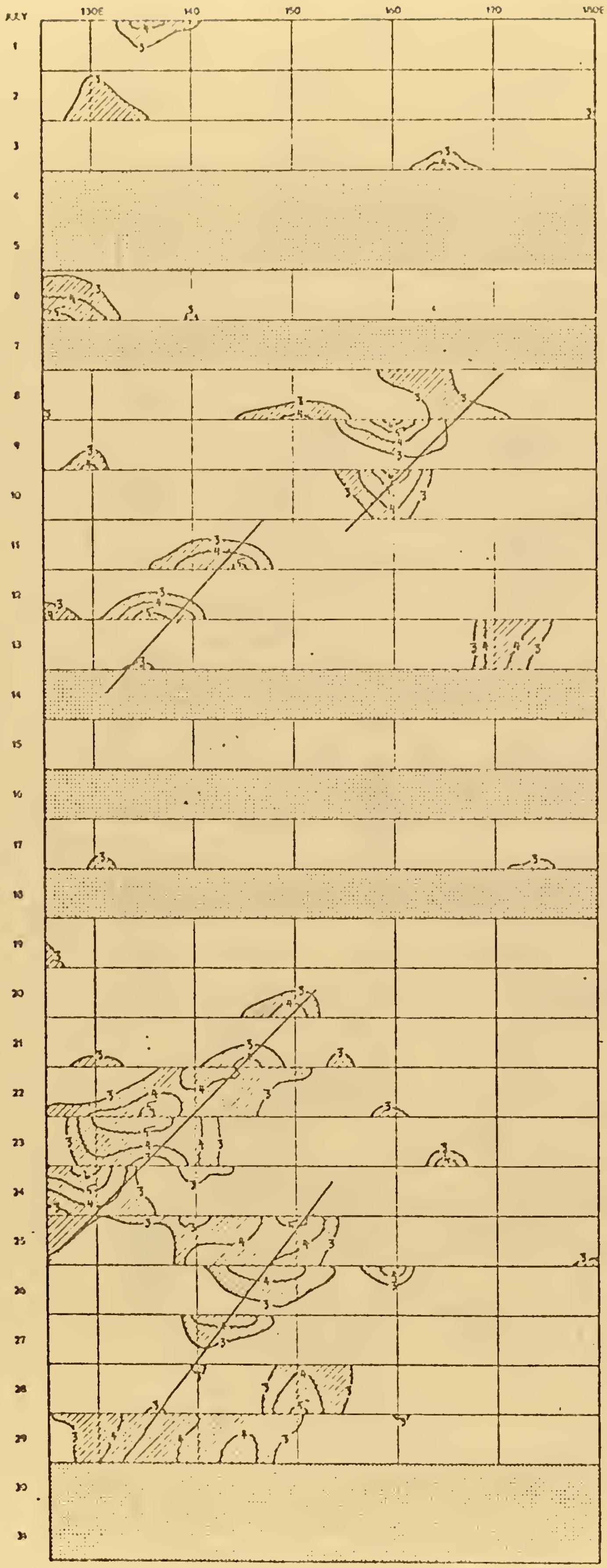

Figure 13. Time-longitude section of cloud brightness for 10° - 15°N latitude band, July 1969.

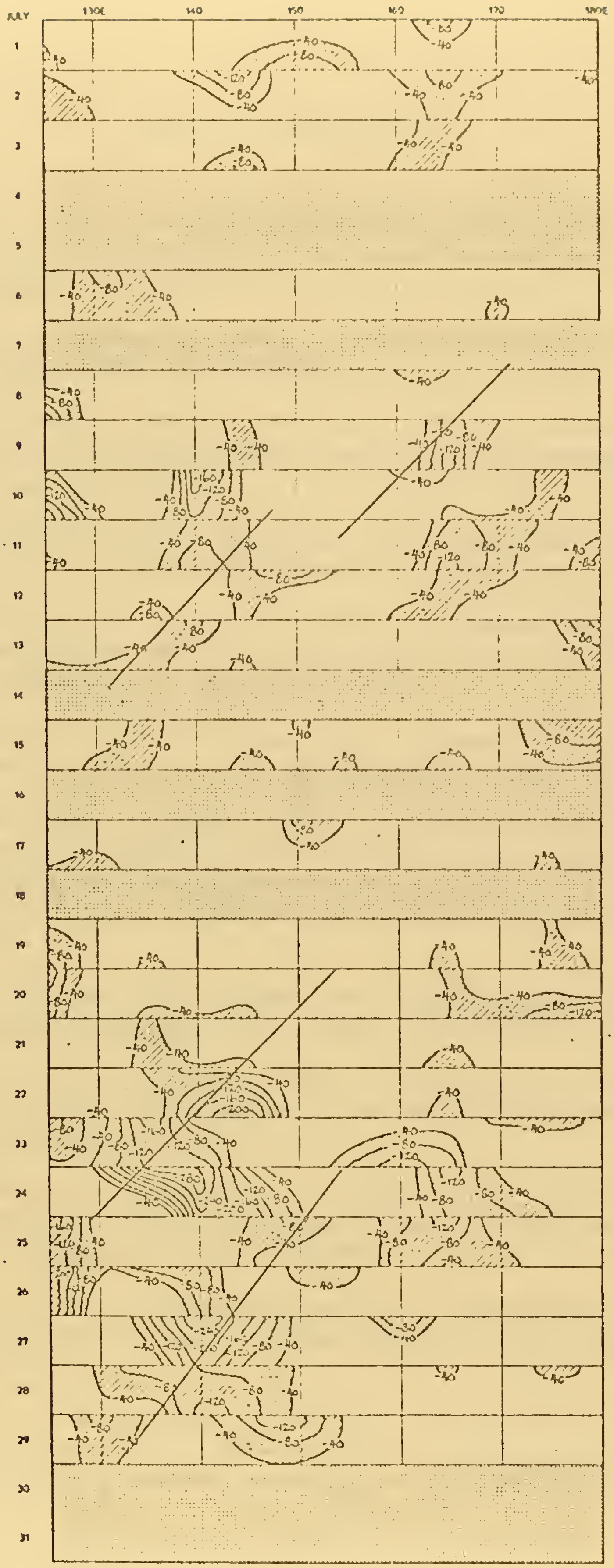

Figure 14. Time-longitude section of upward vertical motion (mb/day) for 10° - 15°N latitude band, July 1969.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Digitized cloud brightness data for July 1969 are examined to determine the degree of relationship between organized brightness patterns and the large-scale convection field in the tropical western North Pacific. Correlation coefficients between kinematically computed vertical motion fields and cloud brightness are generally low, except for a few notable days. This may be due to the quality of the available data, particularly the vertical motion field. Nevertheless, indications of better correspondence between

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the two fields are noted late in the month for the western portion of the region, for the latitude band between 10°N and 20°N.

Examination of time-longitude sections reveals a close association between propagating brightness patterns and vertical motion fields, indicating that the former are reflections of synoptic wave passages, rather than simply inactive clouds advected by zonal flow.

In view of the potential usefulness of such satellite data, a technique is proposed that uses satellite cloud data to objectively determine the large-scale tropical flow.